

LOW POWER AUTO-REFRESH CIRCUIT AND METHOD FOR DYNAMIC RANDOM ACCESS MEMORIES

TECHNICAL FIELD

This invention relates to dynamic random access memories, and, more particularly, to a circuit and method for reducing the power consumed by such memories when operating in an auto-refresh mode.

BACKGROUND OF THE INVENTION

The power consumed by integrated circuits can be a critical factor in their utility in certain applications. For example, the power consumed by memory devices used in portable personal computers greatly affects the length of time they can be used without the need to recharge batteries powering such computers. Power consumption can also be important even where memory devices are not powered by batteries because it may be necessary to limit the heat generated by the memory devices.

In general, memory device power consumption increases with both the capacity and the operating speed of the memory devices. The power consumed by memory devices is also affected by their operating mode. A dynamic random access memory ("DRAM"), for example, will generally consume a relatively large amount of power when the memory cells of the DRAM are being refreshed because rows of memory cells in a memory cell array are then being actuated in the rapid sequence. Each time a row of memory cells is actuated, a pair of digit lines for each memory cell are switched to complementary voltages and then equilibrated, thereby consuming a significant amount power. As the number of columns in the array increases with increasing memory capacity, the power consumed in actuating each row increases accordingly. Power consumption also increases with increases in the rate at which the rows of memory cells are actuated. Thus, as the operating speed and capacity of DRAMs continues to increase, so also does the power consumed increase during refresh of memory cells in such DRAMs.

During a DRAM refresh, power is also consumed by components other than those in the memory cell array. For example, DRAM devices generally include a large number of input buffers to couple a large number of control and address lines to internal circuitry. While the DRAM is being refreshed, these input buffers continue to switch responsive to control and address signals applied to their respective inputs. However, during some refresh modes, control and address signals are not used by the DRAM. In an auto-refresh mode, for example, an auto-refresh command is applied to the DRAM. The DRAM thereafter internally performs a refresh operation for a predetermined period of time. During this period, the DRAM does not respond to control and address signals applied to its input buffers. However, the input buffers continue to switch during this time. Switching these large number of input buffers during an auto-refresh cycle wastes power because, as mentioned above, the signals coupled through the input buffers are not used during an auto-refresh cycle.

In the past, attempts have been made to minimize the power consumption of DRAMs during auto-refresh by removing power to all input buffers except input buffers for clock ("CLK") and clock enable ("CKE") signals. However, leaving the input buffer for the clock active causes the input buffer to consume a significant amount of power during the auto-refresh period since the input buffer toggles with each clock signal transition. Power could be significantly reduced by removing power to the input buffer for the clock signal during the auto-refresh period. But doing so could cause spurious commands to be registered at the conclusion of the auto-refresh period. As is known in the art, memory commands are typically registered by latching command signals into respective latches responsive to one or both edges of the clock signal. If a clock edge occurs during the time that the input buffers for the command signals are being re-powered after the auto-refresh period, a spurious command corresponding to the transitional states of the input buffers may be registered. Although care can be taken to avoid coupling clock signal transitions to a memory device until re-powering of the input buffers have been completed, a spurious clock signal transition may be generated. A spurious clock signal transition can be generated if the clock signal has a high logic level when the input buffer for the clock signal is re-powered.

The spurious clock signal will then register whatever spurious command corresponds to the logic levels at the outputs of the input buffers for the command signals.

In the past, attempts have been made to reduce power during a self-refresh cycle by removing power from the input buffers during the self-refresh period.

5 For a self-refresh command, spurious commands are avoided by first detecting a low-to-high transition of the CKE signal, which signifies the end of the self-refresh. However, the input buffers for the command and address signals are not re-powered at that time. Instead, the output of a small input buffer coupled to the CLK is examined to detect a high-to-low transition of the CLK signal. When the high-to-low transition of the CLK

10 signal is detected, the input buffers for the command and address signals are re-powered so that they will not be in a transitional state by the time the next low-to-high transition of the CLK signal occurs, which is used to register the commands and addresses.

Although the approach described above does reduce power consumption during self-refresh without the risk of registering spurious commands and addresses,

15 this approach is not suitable for use during an auto-refresh cycle. Unlike a self-refresh command, for which the controlling specification allows a delay of two CLK periods to exit the self-refresh cycle, the controlling specification for an auto-refresh command requires the DRAM to be able to register a command occurring on the very next rising edge of the CLK signal. However, the input buffers for the command and address

20 signals may still be in a transitional state at that time, thereby causing spurious command or addresses to be registered.

One approach to minimizing power consumption during an auto-refresh cycle is to remove power from some of the command and address input buffers, but not the input buffers for the clock and clock enable signals, for a predetermined period after

25 the start of an auto-refresh cycle. For example, if an auto-refresh cycle is expected to last 60 nanoseconds, the input buffers might be de-energized for the first 40 nanoseconds. Although this approach does reduce the power consumed during an auto-refresh cycle, it nevertheless still allows a significant amount power to be consumed during the period of time that the input buffers are energized. It is generally not

30 possible to de-energize the input buffers for substantially the entire auto-refresh cycle

because the input buffers must be re-powered well before the end of the auto-refresh cycle and the end of the refresh cycle cannot always be predicted with great accuracy. Thus, de-energizing the input buffers for a predetermined period at the start of each auto-refresh cycle still allows the DRAM to consume a significant amount of power.

- 5 There is therefore a need for a circuit and method that allows a more significant reduction in the power consumed by DRAMs during an auto-refresh cycle without risk of registering spurious commands or addresses.

SUMMARY OF THE INVENTION

- 10 A method and circuit reduces the power consumed by a dynamic random access memory ("DRAM") during an auto-refresh. The DRAM includes a first set of input buffers through which command signals are coupled. The input buffers are disabled during auto-refresh so they do not consume power responding to signals applied to their inputs, and a plurality of command signals are biased to assert a predetermined memory command, such as a "no operation" command. When an
15 internal auto-refresh timer times out, the bias is removed from the command signals, and the input buffers are enabled. In the event the DRAM receives a clock signal, an input buffer through which the clock signal is coupled may also be disabled during the auto-refresh. If so, the input buffer for the clock signal may be re-enabled before re-enabling the input buffers for the command signals so the timing at which the command
20 signal input buffers are re-enabled can be controlled relative to the clock signal. The DRAM may also check the state of a predetermined command signal to transition the DRAM to a low power precharge mode at the conclusion of the auto-refresh.

BRIEF DESCRIPTION OF THE DRAWINGS

- 25 Figure 1 is a block diagram of a conventional memory device in which the inventive power saving circuit can be used.

Figure 2 is a block diagram of one embodiment of a power saving circuit according to the present invention.

Figure 3 is a timing diagram showing various signals present in the power saving circuit of Figure 2.

Figure 4 is a block diagram of another embodiment of a power saving circuit according to the present invention.

5 Figure 5 is a block diagram of still another embodiment of a power saving circuit according to the present invention.

Figure 6 is a block diagram of a computer system using a memory device containing a power saving circuit according to one embodiment of the present invention.

10 DETAILED DESCRIPTION OF THE INVENTION

Figure 1 is a block diagram of a conventional synchronous dynamic random access memory ("SDRAM") 2 that can utilize the present invention, including one or more of the embodiments described herein. However, it will be understood that various embodiments of the present invention can also be used in other types of
 15 DRAMs. The operation of the SDRAM 2 is controlled by a command decoder 4 responsive to high level command signals received on a control bus 6. These high level command signals, which are typically generated by a memory controller (not shown in Figure 1), are a clock enable signal CKE*, a clock signal CLK, a chip select signal CS*, a write enable signal WE*, a row address strobe signal RAS*, a column address strobe
 20 signal CAS*, and a data mask signal DM, in which the "*" designates the signal as active low. The command decoder 4 generates a sequence of command signals responsive to the high level command signals to carry out the function (*e.g.*, a read or a write) designated by each of the high level command signals. These command signals, and the manner in which they accomplish their respective functions, are conventional.
 25 Therefore, in the interest of brevity, a further explanation of these control signals will be omitted.

The SDRAM 2 includes an address register 12 that receives either a row address or a column address on an address bus 14. The address bus 14 is generally coupled to a memory controller (not shown in Figure 1). Typically, a row address is

initially received by the address register 12 and applied to a row address multiplexer 18. The row address multiplexer 18 couples the row address to a number of components associated with either of two memory banks 20, 22 depending upon the state of a bank address bit forming part of the row address. Associated with each of the memory banks
 5 20, 22 is a respective row address latch 26, which stores the row address, and a row decoder 28, which decodes the row address and applies corresponding signals to one of the arrays 20 or 22.

The row address multiplexer 18 also couples row addresses to the row address latches 26 for the purpose of refreshing the memory cells in the arrays 20, 22.
 10 The row addresses are generated for refresh purposes by a refresh counter 30, which is controlled by a refresh controller 32. The refresh controller 32 is, in turn, controlled by the command decoder 4. More specifically, the command decoder 4 applies either an auto-refresh command AREF or a self-refresh command SREF command to the refresh controller 32. As explained above, these commands cause the refresh controller to
 15 refresh the rows of memory cells in the arrays 20, 22 in one of two corresponding modes, namely an auto-refresh mode or a self-refresh mode. In the auto-refresh mode, the refresh controller 32 causes the SDRAM 2 to address each row of memory cells in the array using the refresh counter 30 to generate the row addresses. Thus, as mentioned above, in the auto-refresh mode, it is not necessary for an external device to
 20 apply addresses to the address bus 14 of the SDRAM 2. However, the auto-refresh command must be applied to the SDRAM 2 periodically and often enough to prevent the loss of data stored in the memory cells of the arrays 20, 22. The self-refresh mode is essentially the same as the auto-refresh mode except that it is not necessary to periodically apply a command to the SDRAM 2 from an external device at a rate
 25 sufficient to prevent data loss. Instead, once the refresh controller 32 is placed in the self-refresh mode, it automatically initiates an auto-refresh with sufficient frequency to prevent the loss of data from the memory cells of the arrays 20, 22.

The commands applied to the refresh controller 32 correspond to respective combinations of the command signals applied to the command decoder 4.
 30 These command signals are CS*, RAS*, CAS* and WE*, and CKE. To assert either

the AREF or the SREF command, CS*, RAS*, CAS* must all be active low, and WE* must be inactive high. The CKE signal determines whether the SDRAM 2 will cause the command decoder to generate an auto-refresh command or a self-refresh command. If CKE is high, the command decoder 4 will apply an AREF command to the refresh controller 32. If CKE is low, the command decoder 4 will apply a SREF command to the refresh controller 32. In response to an AREF command, the SDRAM 2 will undergo an auto-refresh cycle and will then wait for another command, which may be another AREF command. In response to an SREF command, the SDRAM 2 will undergo a self-refresh cycle and will continue to do so until the CKE signal transitions high.

After the row address has been applied to the address register 12 and stored in one of the row address latches 26, a column address is applied to the address register 12. The address register 12 couples the column address to a column address latch 40. Depending on the operating mode of the SDRAM 2, the column address is either coupled through a burst counter 42 to a column address buffer 44, or to the burst counter 42 which applies a sequence of column addresses to the column address buffer 44 starting at the column address output by the address register 12. In either case, the column address buffer 44 applies a column address to a column decoder 48, which applies various column signals to corresponding sense amplifiers and associated column circuitry 50, 52 for one of the respective arrays 20, 22.

Data to be read from one of the arrays 20, 22 is coupled to the column circuitry 50, 52 for one of the arrays 20, 22, respectively. The data is then coupled to a data output register 56, which applies the data to a data bus 58. Data to be written to one of the arrays 20, 22 are coupled from the data bus 58 through a data input register 60 to the column circuitry 50, 52 where it is transferred to one of the arrays 20, 22, respectively. A mask register 64 responds to the data mask DM signal to selectively alter the flow of data into and out of the column circuitry 50, 52, such as by selectively masking data to be read from the arrays 20, 22.

One embodiment of a power saving circuit 100 for reducing the power consumption of the SDRAM 2 or some other DRAM during an auto-refresh cycle is

shown in Figure 2. Most of the power saving circuit 100 of Figure 2 is incorporated in the command decoder 4 of the SDRAM 2 of Figure 1, but a portion of the power saving circuit 100 is incorporated in the address register 12. However, it will be understood that the power saving circuit 100 shown in Figure 2 can be placed in other portions of the SDRAM 2 of Figure 1 or in other types of memory devices.

The power saving circuit 100 includes a first set of input buffers 102 that couple the external address bus 14 to an internal address bus 106 to provide a plurality of internal address bits IA_0 - IA_N from corresponding external address bits A_0 - A_N . The input buffers 102 are located in the address register 12, although, as explained above, they may also be located elsewhere. The input buffers 102 are enabled by an active high IBENADD signal. Similarly, a second set of input buffers 110 couple the external control bus 6 to an internal control bus 116 to provide a plurality of internal command signals IC_0 - IC_N from corresponding external command signals. These command signals include an active low address strobe ("RAS*") signal, an active low column address strobe ("CAS*") signal, an active low write enable ("WE*") signal, and an active low chip select ("CS*") signal. An active high clock enable CKE signal is coupled through an input buffer 120 to generate an internal clock enable ("ICKE") signal, and an external clock signal is coupled through an input buffer 124 to generate an internal clock ("ICLK") signal. The input buffers 110 in the second set and the input buffer 124 for the ICLK signal are enabled by an active high IBENCLK signal. The input buffers 110 for the command signals can be switched to a "tri-state" (*i.e.*, a high impedance) condition by a low command input buffer enable IBENCMD applied to the "Z" input of the buffers 110, and to an active low impedance state by a high IBENCMD signal.

The IBENCMD signal is coupled to the gates of several PMOS transistors 130-134, which are coupled between a supply voltage and respective internal command signal lines, and to the input of an inverter 136. The inverter 136, in turn, is coupled to the gate of an NMOS transistor 138, which is coupled between ground and the ICS* signal line. After the input buffers 110 are enabled by a high IBENCLK signal, the IBENCMD signal transitions high to switch the input buffers 110 to a low impedance state and to turn OFF the transistors 130-136 so they do not affect the

operation of the power saving circuit 100. When the input buffers 110 are switched to a high impedance state by a low ^{CLK}IBEN~~CMD~~ signal, the transistors 130-136 are turned ON to bias high respective internal command signal lines to which they are coupled.

The internal command signals IRAS*, ICAS*, IWE*, ICS*, as well as
 5 other internal command signals from the input buffers 110, are applied to a command decoder unit 140. The command decoder unit 140 generates a plurality of memory commands, including an auto-refresh command AREF, from various combinations of the command signals applied to its inputs. As explained above, the AREF command is asserted responsive to decoding IRAS*, ICAS*, and ICS* active low and IWE* inactive
 10 high.

The auto-refresh command AREF is applied to a refresh decoder 150 along with the internal clock ICLK signal and the internal clock enable ICKE signal. Based on the state of the ICKE signal, the refresh decoder 150 determines if the AREF command is for an auto-refresh or if it is for a self-refresh. If ICKE is high, the AREF
 15 command is interpreted as an auto-refresh command, in which case the refresh decoder 150 passes the AREF command to an output terminal as an AREF' command. If ICKE is low, the AREF command is interpreted as a self-refresh command, in which case the refresh decoder 150 generates a SREF command. The refresh decoder 150 command will continue to generate the SREF command until the ICKE signal transitions high.

20 The AREF command is also applied to a timer 154, which generates a T_{OUT} pulse after a predetermined period. The T_{OUT} pulse causes the refresh decoder 150 to terminate the AREF' command, thereby terminating the auto-refresh cycle.

All of the input buffers 110, 120, 124 as well as the transistors 130-136, the inverter 138 the command decoder unit 140, the refresh decoder 150 and the timer
 25 154, are shown in Figure 2 as being located in the command decoder 4. However, as previously mentioned, these components could alternatively be located elsewhere in the SDRAM 2 or in other memory devices.

The operation of the power saving circuit 100 will now be explained with reference to the timing diagram of Figure 3. The combination of control signals
 30 ("CMD") that constitute an auto-refresh AREF command are applied to the SDRAM 2

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 T.C. 10/5/01
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at time T_0 and registered at time T_1 by the rising edge of the external clock CLK signal. The external clock enable CKE signal is high at time T_1 , so the AREF command is registered as an auto-refresh command rather than a self-refresh command. As a result, the command decoder 140 (Figure 2) generates a high AREF signal and the refresh decoder 150 (Figure 2) generates a high AREF' signal, rather than a SREF signal, a short time after T_1 to initiate the auto-refresh cycle. The AREF command generated by the command decoder unit 140 also triggers the timer 154, which will control the duration of the auto-refresh cycle. In response to the initiation of the AREF signal, the refresh decoder 150 also drives the IBENADD, IBENCMD and IBENCLK signals low, thereby disabling the input buffers 102, 110, 124. The input buffers 102, 110, 124 will thereafter not respond to signal transitions applied to their respective inputs so that they will not consume power even if the signal transitions are rapidly occurring. As a result, the SDRAM 2 consumes relatively little power during the auto-refresh mode. The low IBENCMD signal turns ON the transistors 130-136 thereby maintaining the IRAS*, ICAS*, IWE* signals high and the ICS* signal low during the auto-refresh cycle. Driving these signals in this manner asserts a no operation ("NOP") command. However, since the clock input buffer 124 was disabled by IBENCLK transitioning low at time T_1 , the command decoder unit 140 does not register and decode these signals as a no operation ("NOP") command.

The timer 154 generates a T_{OUT} pulse at time T_2 thereby causing the refresh decoder 150 to transition the AREF' signal low to terminate the auto-refresh cycle. The refresh decoder 150 also drives the IBENCLK signal high at time T_2 to couple the CLK signal through the input buffer 124. If the external clock CLK signal is low at time T_2 , enabling the input buffer 124 will have no effect until the next rising edge of the CLK signal. However, if the CLK signal is high at time T_2 , enabling the buffer 124 at time T_2 will cause the ICLK signal at the output of the input buffer 124 to transition at time T_2 , which will register the command signals at the output of the input buffers 110 as a valid memory command. However, since the IBENCMD is still low at time T_2 , the memory command is registered as a NOP command, which will not cause the SDRAM 2 to perform any memory operation. Significantly, the spurious rising

ICLK edge will not cause the SDRAM 2 to register a spurious command, which might occur if the IRAS*, ICAS*, IWE*, ICS* signals were not biased to a NOP command. The refresh decoder 150 transitions the IBENCMD signal high a period of time after the IBENCLK signal transitions high. The high IBENCMD signal switches the outputs of the input buffers 110 for the command signals to a low impedance state and turns OFF the transistors 130-136 so the IRAS*, ICAS*, IWE* signals are no longer biased high and the ICS* signal is no longer biased low. As shown in Figure 3, the refresh decoder 150 also transitions the IBENADD signal high at time T₃, although it could transition the IBENADD signal high at time T₂ or some other time.

The power saving circuit 100 thus reduces the power consumed by the SDRAM 2 during an auto-refresh cycle, and it does so in a manner that avoids the possibility of a spurious memory command being registered responsive to the input buffers 100 for the command signals being enabled at the conclusion of the auto-refresh period.

Another embodiment of a power saving circuit 200 is shown in Figure 4. The power saving circuit 200 is substantially identical to the power saving circuit 100 shown in Figure 2, and it operates in substantially the same manner. Therefore, in the interest of brevity, the circuit components used in the power saving circuit 200 that are identical to the circuit components used in the power saving circuit 100 have been provided with the same reference numerals, and an explanation of their operation will not be repeated. The power saving circuit 200 differs from the power saving circuit 100 by using a permanently enabled input buffer 220 to generate the internal clock ICLK signal from the external clock CLK signal. The power saving circuit also includes an internal clock buffer 230 that is enabled by the IBENCLK signal.

The operation of the power saving circuit 200 is substantially the same as the power saving circuit 100. Specifically, in response to registering an AREF command, the IBENCMD, IBENADD and IBENCLK signals transition low to disable the input buffers 102, 110 and the internal clock buffer 230. As a result, neither the input buffers 102, 110 nor circuitry (not shown) downstream from the internal clock buffer 230 consume power during the auto-refresh cycle initiated in response to the

AREF command. However, the input buffer 220 for the clock signal and circuitry in the refresh decoder 150 that responds to the ICLK signal will consume power during the auto-refresh cycle. When the timer 154 times out to generate the T_{OUT} pulse, the refresh decoder 150 can simply wait for half the period of the ICLK signal after the preceding rising edge of the ICLK signal to transition the IBENCMD, IBENADD and IBENCLK signals high. The power saving circuit 200 thus has the disadvantage of consuming more power than the power saving circuit 100 of Figure 2, but it has the advantage of being able to enable the input buffers 102, 110 without generating a spurious command.

Another embodiment of a power saving circuit 300 is shown in Figure 5.

10 The power saving circuit 300 is also very similar to the power saving circuit 100 shown in Figure 2, and it initially operates in substantially the same manner. Therefore, in the interest of brevity, the circuit components used in the power saving circuit 300 that are identical to the circuit components used in the power saving circuit 100 have been provided with the same reference numerals, and an explanation of their operation will not be repeated. The power saving circuit 300 differs from the power saving circuit 100 by allowing the SDRAM 2 to operate in a mode that automatically transitions the SDRAM 2 to a power saving precharge mode at the conclusion of a reduced power auto-refresh cycle. In addition to the components used in the power saving circuit 100 of Figure 2, the power saving circuit of Figure 5 includes a mode decoder 310 that
20 decodes the CKE signal and a data mask ("DM") signal applied to a DM input terminal. As explained above, the DM signal is used to mask data being read from or written to the SDRAM 2. Thus, the DM terminal is not needed during a refresh of the SDRAM 2 because data are not being read from or written to the SDRAM 2. Although the DM input terminal is used in the embodiment shown in Figure 5, it will be understood that
25 some other terminal that is not used during refresh may be used to assert an auto-refresh command.

The mode decoder decodes these signals as follows:

MODE	DM	CKE
Low Power AREF Mode With Low Power Precharge	"0"	"0" (for full AREF period)

ICLK signal
AB 10/05/01
T.C. 10/5/01
R.M.S. 10/5/01

Low Power AREF Mode Without Low Power Precharge	"0"	"1"
Normal AREF Mode	"1"	"0"
Normal SREF Mode	"1"	"1"

Thus, if the DM signal is high when the AREF or SREF commands are asserted, the SDRAM 2 operates in a conventional manner. However, if the DM signal is low when the AREF command is asserted, the SDRAM 2 operates in the low power AREF mode described above with reference to Figures 2 and 3 regardless of the state of the CKE signal. If the CKE signal is high when the AREF command or at any time during the auto-refresh, when the T_{OUT} pulse is generated to end of the AREF cycle, the SDRAM 2 returns to its normal operating mode to wait for another memory command. However, if the CKE signal is low when the AREF command is asserted and remains low during the entire auto-refresh cycle, the refresh decoder 150' generates an active high low power precharge ("LPP") signal when the T_{OUT} pulse is generated to end of the AREF cycle. Also, in the low power precharge mode, the SDRAM 2 remains in the low power AREF mode so that the refresh decoder 150' does not transition the IBENCMD, IBENADD and IBENCLK signals high at the end of the AREF cycle. Circuitry in the SDRAM 2 (not shown) responds to the high LPP signal to remove power from circuit components in the SDRAM 2 that need not be powered to retain data stored in the memory arrays 20, 22 (Figure 1). For example, power may be removed from the command decoder 4 (Figure 1), the column decoder 48, and some of the row decoders 28.

The SDRAM 2 remains in the low power AREF mode as described above and in the low power precharge mode until the CKE signal transitions high. Also, as mentioned previously, if the CKE signal transitions high at any time during the AREF cycle, the active high LPP signal will not be generated at the end of the AREF cycle. When the CKE signal transitions high, the refresh decoder 150' transitions the IBENCMD, IBENADD and IBENCLK signals active high as described above. The refresh decoder 150' also transitions the LPP signal inactive low to re-apply power to circuitry in the SDRAM 2. The low power AREF mode with the LPP mode thus not

only minimizes the power consumed by the SDRAM 2 during an auto-refresh cycle, but it also automatically switches the SDRAM 2 to an operating mode at the end of the auto-refresh cycle in which even less power is consumed.

Although the power saving circuit 300 shown in Figure 5 uses the DM
 5 signal to differentiate between low power auto-refresh modes with and without the low power precharge mode, other means of differentiating between these modes can be used. For example, a conventional mode register (not shown) could be programmed with one or more bits during initialization of the SDRAM 2 to indicate a selected operating mode.

10 Figure 6 shows an embodiment of a computer system 400 that may use the SDRAM 2 or some other memory device that contains an embodiment of a power saving circuit as described herein or some other embodiment of a power saving circuit in accordance with the invention. The computer system 400 includes a processor 402 for performing various computing functions, such as executing specific software to
 15 perform specific calculations or tasks. The processor 402 includes a processor bus 404 that normally includes an address bus, a control bus, and a data bus. In addition, the computer system 400 includes one or more input devices 414, such as a keyboard or a mouse, coupled to the processor 402 to allow an operator to interface with the computer system 400. Typically, the computer system 400 also includes one or more output
 20 devices 416 coupled to the processor 402, such output devices typically being a printer or a video terminal. One or more data storage devices 418 are also typically coupled to the processor 402 to store data or retrieve data from external storage media (not shown). Examples of typical storage devices 418 include hard and floppy disks, tape cassettes, and compact disk read-only memories (CD-ROMs). The processor 402 is also typically
 25 coupled to a cache memory 426, which is usually static random access memory ("SRAM") and to the SDRAM 2 through a memory controller 430. The memory controller 430 includes an address bus coupled to the address bus 14 (Figure 1) to couple row addresses and column addresses to the DRAM 2, as previously explained. The memory controller 430 also includes a control bus that couples command signals to
 30 a control bus 6 of the SDRAM 2. The external data bus 58 of the SDRAM 2 is coupled

to the data bus of the processor 402, either directly or through the memory controller 430. The memory controller 430 applies appropriate command signals to the SDRAM 2 to cause the SDRAM 2 to operate in one or more of the power saving modes described above.

- 5 From the foregoing it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the invention. Accordingly, the invention is not limited except as by the appended claims.

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